

**INTRODUCTION**

The San Sebastián quadrangle is divided into two tectonostratigraphic provinces representing periods in the development of Puerto Rico: 1) folded, faulted and weakly metamorphosed volcanogenic rocks representing orogenic activity during Late Cretaceous-early Tertiary time; and 2) very gently dipping, weakly deformed to undeformed limestone and epiclastic sedimentary rocks, representing a period of relative orogenic quiescence during the late Oligocene and Miocene. The middle Tertiary rocks have been studied in the field by the present authors and by W. H. Monroe, but no extensive laboratory studies have been carried out. The volcanogenic rocks, however, have been subjected to considerable field and laboratory work, and most of the following discussion is concentrated on these rocks.

We wish to thank Emile A. Passaglia, Jr., Geosciences Division, Graduate Research Center, Dallas, Texas, and K. N. Sachs, Jr., U.S. Geological Survey, for dating Foraminifera from several formations in the San Sebastián quadrangle. Thanks are also extended to Rigoberto Reynoso, formerly resident geologist with Bear Creek Mining Company in Lares, Puerto Rico, who gave freely of his time in discussing the many problems encountered in the field.

**STRATIGRAPHY AND MINERALOGY OF VOLCANOGENIC ROCKS**

The general characteristics of the individual formations have been outlined in some detail elsewhere (Nelson and Tobisch, 1967; McIntyre and others, 1970), and only certain noteworthy aspects of the volcanogenic rocks will be discussed here.

The volcanogenic rocks in the quadrangle are divided into two parts separated by the Añasco fault. The Rio Blanco Formation and Concepción Formation (McIntyre and others, 1970) lie south of the fault; the Mal Paso, Rio Culebrinas (McIntyre and others, 1970), Milagros, and Matilde Formations (Nelson and Tobisch, 1967) lie to the north. Rocks south of the fault range in age from Late Cretaceous to early Tertiary (Williams and others, 1970) and are characterized by incipient greenschist facies metamorphism; those to the north are early Tertiary in age and are characterized by incipient zeolite facies metamorphism.

**Concepción and Rio Blanco Formations.**—The Concepción Formation is characterized by lava flows and thin-bedded volcanoclastic sedimentary rocks. The Rio Blanco Formation consists chiefly of massive tuff-breccia and lapilli tuff. Both formations are andesitic to dacitic in composition.

The rocks have been recrystallized, and primary textures and minerals are generally modified to varying extent. Plagioclase, hornblende, and clinopyroxene are the primary minerals in rocks of both formations. The proportions of these minerals vary greatly, but plagioclase, along with optically unresolvable material, is generally dominant and forms the bulk of the rock. Plagioclase ranges from albite to andesine, but commonly is altered to epidote or clay mineral(s). The primary plagioclase was undoubtedly more calcic than albite, but recrystallization has yielded more sodic varieties. Where present, hornblende and pyroxene are also generally altered to varying extent. Primary and secondary minerals which commonly make up nearly half the rock include epidote minerals, chlorite, calcite, sericite(?) and quartz. These minerals generally form pseudomorphs after the primary minerals. Prehnite and, rarely, laumontite have also been observed.

**Mal Paso Formation.**—The Mal Paso Formation occurs north of the Añasco fault. It is distinguished from the other formations north of the fault by its red-purple color as well as by its mineralogy. Tuff breccias, lapilli tuff and lava flows of the Mal Paso Formation are highly scoriaceous. The vesicles are commonly filled with calcite, quartz, zeolite mineral(s) and bright-green celadonite(?). The tuff breccia and lapilli tuff are deeply weathered, and could not be sampled for thin section analysis. This section of vesicular lava flows show calcic plagioclase, however, and this evidence coupled with chemical analysis indicates the rock is a basalt. Another rock type which occurs in the Mal Paso Formation along Highway 119, may be a lava flow, sill, or dike. It shows a porphyritic texture in thin section, with a groundmass of albite microclites, magnetite and lesser hematite after the primary minerals. Prehnite and, rarely, laumontite have also been observed.

**Rio Culebrinas, Milagros and Matilde Formations.**—The Rio Culebrinas, Milagros and Matilde Formations consist of thin-bedded tuffs and fine- to medium-grained volcanic sandstones and massive tuff breccias. Lava flows are not common.

These rocks are typically andesite to dacitic in composition. They contain plagioclase (commonly calcic labradorite, but ranging from andesine to bytownite), hornblende, and pyroxene in varying amounts. Primary quartz is relatively common in the Rio Culebrinas Formation, but is found only in sparse amounts in the Milagros and Matilde Formations. Many of the thin-bedded tuffs in the Rio Culebrinas Formation contain crystal fragments of plagioclase, pyroxene and hornblende, along with lapillized fragments of plagioclase, hornblende, or pyroxene-bearing porphyry. Optically unidentifiable fragments, and rarely pumices, are other rock constituents. The plagioclase in the rocks is commonly slightly to moderately altered to clay mineral(s). The pyroxene in rocks of these three formations is typically a colorless clinopyroxene; however, in the Milagros Formation, especially in the breccia member, both orthopyroxene and clinopyroxene coexist in the same rock. Secondary minerals include laumontite, heulandite, analcime, celadonite(?), chlorite, quartz, stilpnomelane, calcite and rare epidote, which range in volume up to several percent from specimen to specimen.

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Williams, Howard, Turner, F. J., and Gilbert, C. M., 1955, between the Rio Culebrinas and Matilde Formations, is most probably also middle Eocene.

**INTRUSIVE ROCKS**

The Concepción and, to a lesser extent, the Rio Blanco Formations have been intruded by small dioritic and quartz diorite bodies ranging in size from dikes a few meters or more across to stocks nearly a kilometer across. In the eastern part of the Concepción Formation, these igneous bodies appear to have a close spatial (and possibly genetic) relationship to the lava flows. Chemical analysis of one lava flow (for dike) from the Concepción Formation showed a high content of Na<sub>2</sub>O (6.3 percent), but this may not be typical of the lavas. Often the textural variation between intrusive bodies and lava flows in this area is so erratic that it is difficult to distinguish them. The volcanogenic rocks, however, have been subjected to considerable field and laboratory work, and most of the following discussion is concentrated on these rocks.

The mineralogy of the intrusive bodies consists essentially of plagioclase, hornblende and, rarely, clinopyroxene. Plagioclase (andesine) is the predominant primary mineral, and is moderately to strongly altered. The hornblende is colorless to pale green and may be in part an alteration product of primary hornblende or pyroxene. Clinopyroxene, however, has been observed only in one small plug within the Rio Blanco Formation. Secondary minerals of the intrusive bodies include epidote, chlorite, calcite and rarely, prehnite. Pyrite and magnetite are common accessories, but within the general area of Barrio Puntano, Concepción, pyrite often occurs disseminated throughout the intrusive bodies in larger amounts than is generally found elsewhere.

**TECTONIC STRUCTURES**

The middle Tertiary formations (Rio Guatemala Group) strike east and dip 5° to 8° to the north. These rocks appear to be little deformed, although there is some evidence that faulting may offset the Lares Limestone in the Rio Guatemala north of San Sebastián (W. H. Monroe, 1967, written commun.) and in the Rio Guaitaca northwest of Lares; minor faulting occurs elsewhere. The extraordinary topographic lineations in the Lares Limestone (note the distinct geomorphic features north of Lares; see Monroe, 1964, p. B126-B129) that strike northwest and, to a lesser degree, northeast are noteworthy. It is possible that the principal structural directions of the underlying volcanogenic rocks, which also trend northwest with subordinate northeast directions, have influenced the directions of joint pattern formation in the limestone (compare Hodgson, 1965).

The Upper Cretaceous and lower Tertiary rocks have a general northwest strike and dip is generally north (south of the Añasco fault) or south (north of the Añasco fault), as shown in section *B-B'*. The Rio Blanco, the eastern part of the Concepción, and the Milagros Formations do not show much structural (tectonic) complication. This may be due to the sluggish response of the massive formations to internal deformation, as well as to the lack of marker horizons to record the deformation. On the other hand, the thin-bedded rocks in the western part of the Concepción Formation, which also trend northwest with subordinate northeast directions, have influenced the directions of joint pattern formation in the limestone (compare Hodgson, 1965).

The Añasco fault and its subsidiary faults are the most prominent structural features in the quadrangle. They cut across the strike of both Upper Cretaceous and lower Tertiary formations. Evidence for apparent sense of horizontal movement along the Añasco fault in the San Sebastián quadrangle is equivocal. To the west in the Central La Plata dome, the strike-slip fault is generally north-south, and the Añasco fault appears to be left lateral (D. H. McIntyre, 1967, oral commun.). A component of vertical movement is also likely. The dip of the Añasco fault plane in the San Sebastián quadrangle was determined by measuring these structures in the fault zone. These surfaces have consistently steep outward dip of 60° to 70° across the quadrangle. The large fault just to the north has a steeper dip, probably between 80° and 90°. Other faults in the quadrangle appear to be essentially vertical.

Folding occurs on a significant scale in the Rio Culebrinas Formation. The folds plunge 5° to 30° to the north-west in most areas, but in the general area of Quebrada Las Cañas, individual folds locally reverse their plunge, alternating between northwest and southeast. If marker horizons were available, they would delineate elongate basins, domes and other culmination patterns. These doubly-plunging structures may have been formed by variations in compressive strain causing the fold axes to buckle (Tritt, 1964, p. 257-258; Ramsay, 1962, fig. 19).

One of the more enigmatic structures occurs between the Mal Paso Formation and the Rio Culebrinas Formation. The structure is defined by a zone of disturbance in which the bedding orientation is highly erratic over short distance, and by graded bedding with tops toward the center of the disturbed zone on both sides. These facts suggest that the structure is an overturned syncline which may have sustained a certain amount of rupture parallel to its axial plane in such a way that the movement was distributed over a wide disturbed zone. The syncline is nearly isoclinal in the east (section *B-B'*), but grades to a tight style toward the west (section *A-A'*). In the Central La Plata quadrangle, the structure reverts to a normal upright syncline and has an open style (D. H. McIntyre, 1967, oral commun.).

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The volcanogenic rocks in the quadrangle are divided into two parts separated by the Añasco fault. The Rio Blanco Formation and Concepción Formation (McIntyre and others, 1970) lie south of the fault; the Mal Paso, Rio Culebrinas (McIntyre and others, 1970), Milagros, and Matilde Formations (Nelson and Tobisch, 1967) lie to the north. Rocks south of the fault range in age from Late Cretaceous to early Tertiary (Williams and others, 1970) and are characterized by incipient greenschist facies metamorphism; those to the north are early Tertiary in age and are characterized by incipient zeolite facies metamorphism.

**Concepción and Rio Blanco Formations.**—The Concepción Formation is characterized by lava flows and thin-bedded volcanoclastic sedimentary rocks. The Rio Blanco Formation consists chiefly of massive tuff-breccia and lapilli tuff. Both formations are andesitic to dacitic in composition.

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